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PERFORMANCE LIMITS OF GRAVITY-ASSIST HEAT PIPES WITH SIMPLE WICK STRUCTURES

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ABSTRACT

Experiments using gravity-assist heat pipes with simple wick structures were used to establish performance limits due to entrainment of the liquid by the counter-flowing vapor. A physical model is postulated which leads to a single correlation predicting entrainment limits for all data investigated. The characteristic length in the entrainment parameter is the depth of the wick structure and the model infers an upper bound on this parameter.

NOMENCLATURE

A	heat pipe vapor flow area
C	correlation coefficient
D	heat pipe diameter
E_t	dimensionless entrainment parameter
F_D	inertia force
F	surface tension force
h_{fg}	latent heat of vaporization
Q_E	dimensionless power
q	heat pipe power
V	velocity
W_e	Weber number
[illegible]	velocity profile correction factor
[illegible]	surface depth
[illegible]*	reference surface depth
[illegible]	vapor density
[illegible]	surface tension

INTRODUCTION

Recent emphasis on energy conservation has resulted in widespread interest in thermal recovery units particularly in medium to high temperature applications. The superior performance characteristics of heat pipes can be used to advantage in these systems if fabrication costs are kept low. Consistent with a low cost goal, gravity-assist heat pipes or thermosyphons with simple wick structures are promising candidates for heat recovery systems. A fundamental understanding of the performance limitations of these systems is required.

The performance limits in gravity-assist heat pipes with capillary flow where no excess liquid is present has been addressed by Busse and Kemme.[1] They derive performance limits due to axial and azimuthal dryout of the wick. The technique of overfilling gravity-assist heat pipes results in excess liquid which is returned to the evaporator outside the heat pipe wick structure. The interaction with the counterflowing vapor may give rise to entrainment of the liquid. Interruption of the liquid return causes evaporator dryout resulting in a performance limit. Cotter[2] first suggested that this limit was related to the Weber number, a ratio of inertia to surface tension forces. The problem arises in defining an appropriate characteristic length when formulating the surface tension force. Kemme[3] has reported success when using a length equal to the wire diameter plus the distance between wires on heat pipes with screened wicks. This paper presents additional performance limit data obtained from several gravity assist heat pipes. This data together with other data[3,4] obtained from the literature is used as a basis for an entrainment limit correlation where the characteristic dimension is the depth or amplitude of the wick structure.

EXPERIMENTS

Several gravity-assist heat pipes have been constructed and tested. Their principal characteristics are listed in Table 1. In the first series of tests, a simple, homogeneous, screened wick consisting of two layers of 150-mesh screen was used. This heat pipe was tested with water, methanol, and toulene working fluids and is designated as BES3W, BES3M, and BES3T. At low temperatures the effects of liquid inventory and tilt were investigated and have been reported.[5] Performance limits at higher temperatures are attributed to either boiling limitations in the evaporator or to entrainment between the counterflowing liquid and vapor.

Tests have also been conducted on a 3-m-long steel heat pipe using mercury as the working fluid. The internal surface of this heat pipe is threaded, which serves to circumferentially distribute the working fluid. This pipe has been tested at temperatures up to 400°C and the data are referred to as BES4HG.

In addition, tests were conducted on knurled heat pipes using both liquid metal and organic working fluids. The depth and pitch of the knurls were varied to provide a range of surface conditions. Coarse knurls were tested using sodium and are designated as BES5NA while fine knurls were tested with methanol and are identified as BES6M. Additional tests are planned with these heat pipes. Two other sets of data are included; one using a knurled surface[4] with mercury as the working fluid and one using sodium in a graded, screened wick configuration.[3]

Data were obtained for each heat pipe at various elevation angles and with liquid inventories ranging from 50-400 cm^3. Only the data for elevation angles of 90 deg (vertical with evaporator below condenser) are reported. It has been observed[5] that a transition from film flow, where the heat pipe walls are uniformly coated with liquid, to puddle flow occurs at elevation angles below 90 deg. This transition is usually accompanied by an increase in heat pipe performance. This discussion will be restricted to film flow only. Heating was supplied with induction coils and cooling was provided by either a gas-gap calorimeter or a direct-contact calorimeter. For the high-temperature working fluids the gas-gap method was used with provision to vary the mixture of helium and argon to effect

Table 1 Summary of Gravity-Assist Heat Pipe Dimensions

Identification	Working Fluid	I.D. (cm)	Length (cm)	Type of Wick	Characteristic Depth of Wick (cm)	Characteristic Length of Wick (cm)	Source of Data
BES3W	water	2.16	80	screen	0.0033	0.0167	5
BES3M	methanol	2.16	80	screen	0.0033	0.0167	5
BES3T	toluene	2.16	80	screen	0.0033	0.0167	5
BES4HG	mercury	3.35	330	threads	0.0279	0.0279	present paper
HEDL	mercury	4.50	350	knurls	0.0254	0.130	4
BES5NA	sodium	3.20	80	knurls	0.051	0.191	present paper
SEPNA	sodium	2.30	315	screen	0.0216	0.159	3
BES6M	methanol	3.20	80	knurls	0.015	0.075	present paper

a variable thermal coupling with the water-cooled calorimeter. The low temperature heat pipes used a direct-contact, water-cooled calorimeter and adjustment of coolant inlet temperature to the calorimeter was provided. All heat pipes contained adiabatic zones instrumented with wall-mounted thermocouples. Power transported by the heat pipe was measured at the calorimeter using coolant flowrate and temperature rise measurements.

Performance limits are defined as operating points where the heat pipe is no longer substantially isothermal. For heat pipes with constant heat flux boundary conditions, as in these tests, limits are well defined. A sudden and rapid increase in one or more evaporator thermocouple readings is observed when a limit is reached. In most cases either an increase in heat pipe temperature or a decrease in power would restore the heat pipe to nearly isothermal conditions. This behavior is characteristic of a vapor dominated limit giving further evidence of entrainment behavior in the heat pipe.

A physical model describing the entrainment phenomena is presented in the following section. This model defines appropriate correlating parameters for use in analyzing the test data. Using the available experimental data as a basis, a general entrainment limit correlation is proposed.

PHYSICAL MODEL

The power transported by the heat pipe is limited by entrainment of the returning liquid by the counterflowing vapor. The physical model assumes a uniform liquid layer returning along the heat pipe wall. As the mechanical interaction with the counterflowing vapor increases, an instability in the liquid surface[6] develops resulting in wave formation. The friction increases rapidly under these conditions and liquid droplets are torn from the wave crests preventing liquid return to the heat pipe condenser. It is postulated that the wave formation at the liquid surface is influenced by the geometry of the underlying surface. The forces arising from the physical interaction between the liquid and vapor are illustrated in Fig. 1. The inertia force of the vapor retards the liquid flow and is counteracted by the surface tension of the liquid or

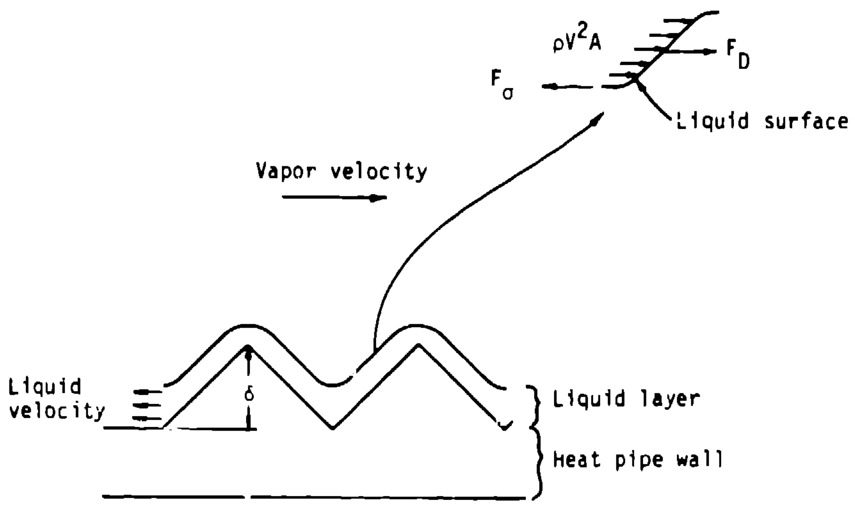

Fig. 1. Force balance on a wave segment.

$$F_D = F_\sigma . \tag{1}$$

Assuming that the liquid wave height is governed by the underlying surface, i.e., the height of the liquid wave equals the surface roughness, an expression for the inertia force can be obtained

$$F_D = \pi D \delta \rho V^2 . \tag{2}$$

Likewise for the surface tension force

$$F_\sigma = \pi D \sigma . \tag{3}$$

Define an entrainment parameter as the ratio of these forces and note it is an inverse Weber number

$$E_t = \frac{F_\sigma}{F_D} = \frac{\sigma}{\rho V^2 \delta} . \tag{4}$$

The empirical data show and the physical model indicates that δ is a depth associated with the wick structure. In the case of knurls or threads δ is the depth of the cut. However, for screen wicks δ is one-half the wire diameter of the innermost screen layer. Apparently only the convergent part of the volume between wires governs the wave formation at the liquid-vapor interface.

The velocity term in Eq. (4) can be eliminated by noting that ρV^2 is the inertial force per unit area and equals the power divided by the volumetric flow in the heat pipe or

$$\rho V^2 = \frac{q}{A\overline{V}} . \tag{5}$$

where δ has units of cm. Equation (13) is made dimensionless by introducing a reference depth δ^* and Eq. (13) becomes

$$Q_e = C' E_t^{1/2} \delta/\delta^* . \tag{14}$$

In the following section a physical interpretation of δ^* is suggested.

Interpretation of the Reference Length, δ^*

By introducing a Weber number[7]

$$W_e = \frac{\alpha \rho V^2}{2\pi\sigma/\delta} , \tag{15}$$

where α is a velocity profile correction factor,[8] and defining the onset of entrainment when

$$W_e = 1 , \tag{16}$$

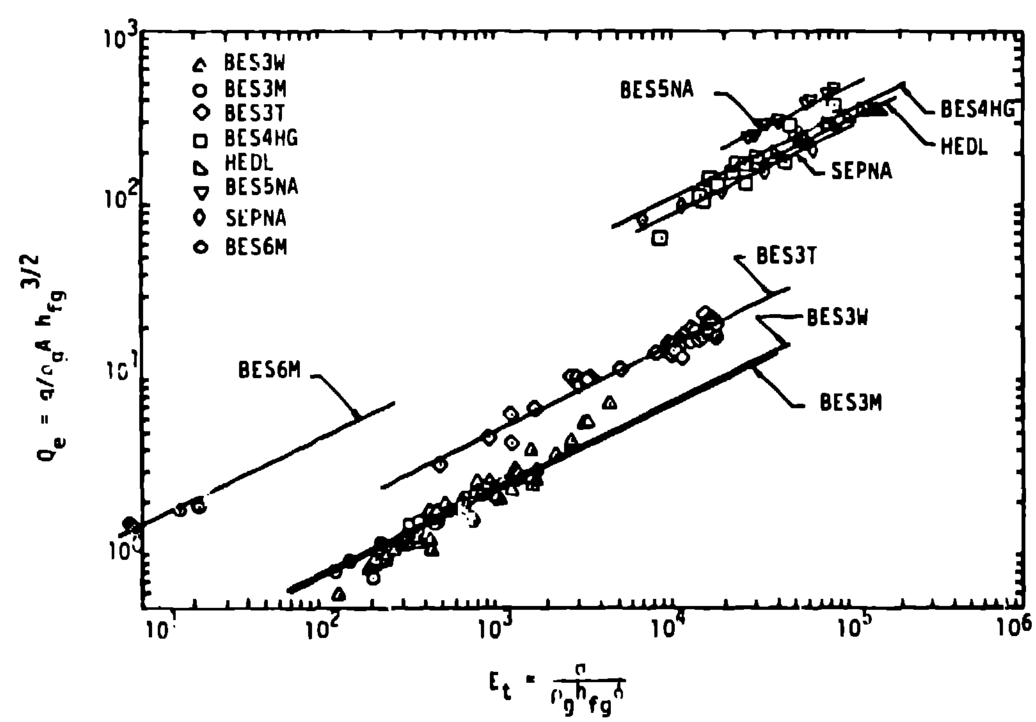

Fig. 2. Dimensionless power for heat pipe entrainment limit.

Table 2 Entrainment Limit Correlation Coefficients*

Heat Pipe Identification	Working Fluid	Coefficients, C
BES3W	water	0.075
BES3M	methanol	0.072
BES3T	toluene	0.157
BES4HG	mercury	1.06
HEDL	mercury	0.968
BES5NA	sodium	1.53
SEPNA	sodium	0.884
BESGM	methanol	0.469

*$C = Q_e / E_t^{1/2}$

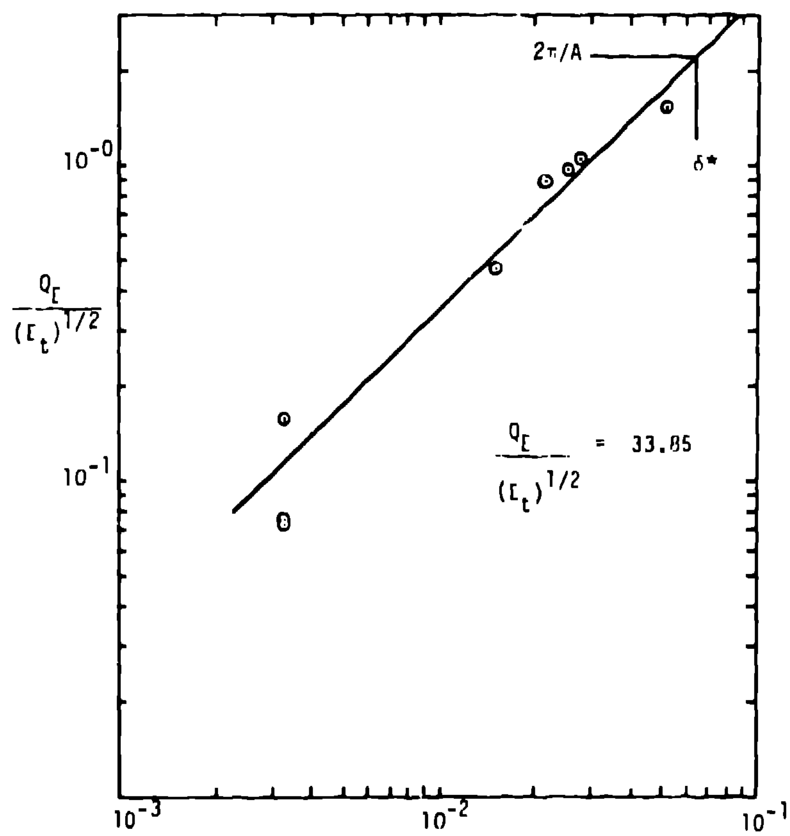

Fig. 3. Geometry dependence on entrainment limit.

then

$$\frac{\rho V^2}{\sigma/\delta} = \frac{2\pi}{\alpha} \ . \tag{17}$$

Using continuity along with Eqs. (7) and (10)

$$Q_e = \sqrt{2\pi/\alpha}\, E_t^{1/2} \ . \tag{18}$$

Equations (14) and (18) can be made identical if

$$C' = \sqrt{2\pi/\alpha} \tag{19}$$

and

$$\delta^* = C'/33.8 \text{ cm} \ . \tag{20}$$

For laminar flow $\alpha = 1.234$ and therefore $\delta^* = 0.067$ cm.

The dimensionless depth δ^* may correspond to a critical depth beyond which the effect of the underlying surface may not be important. This implies an upper limit to the correlation shown in Fig. 3. At

$$\delta/\delta^* = 1 \ ,$$

then

$$\frac{Q_e}{E_t^{1/2}} = \sqrt{2\pi/\alpha} \ . \tag{21}$$

Since none of the heat pipes tested had surface geometries with

$$\delta < 0.067 \text{ cm} \ ,$$

the existence of this upper bound has not been experimentally verified.

DISCUSSION

The entrainment limit correlation predicts an increase in the performance limit as the characteristic depth of the underlying surface is increased. This result is contrary to the results of the physical model shown by Eq. (11) and also represents a departure from results of previous investigations.[9] Examination of the data in Fig. 2 illustrates the dependence on surface depth. The two mercury heat pipes, BES4HG and HEDL, have similar characteristic depths but differ greatly in characertistic length. However, they have similar performance limits. A comparison of the two heat pipes containing methanol shows an increase in the entrainment limit with increasing depth. Also, the data for BES3T, shown in Fig. 2, should agree with data from BES3W and BES3M since the data represent the same heat pipe. We suspect the physical property data for toluene to be the cause of the discrepancy.

As discussed earlier we postulate an upper limit to the surface depth beyond which a further increase in performance would not be expected. It would appear from physical arguments that the liquid layer thickness would influence the critical depth, δ^*. Hence, the success of the correlation using a constant δ^* is surprising since the liquid layer thickness at the entrainment limit would be different for each working fluid. However, the thickness of the liquid layers does not vary appreciably, being greater than 0.01 cm but less than 0.015 cm.

In the case of screened wicks the characteristic depth is one-half the wire diameter of the layer adjacent to the vapor passage. The one-half may be related to intermeshing of the screen layers which reduces their effective depth. Experiments with heat pipes incorporating a single layer of screen may clarify this effect. No assessment is made of the possible degradation in heat pipe performance due to nonuniform liquid distribution on the evaporator wall. The use of coarse wick structures promotes surface hot spots which may be a limiting factor in wick design. It appears that the graded wick arrangement, with fine wire next to the wall and progressively coarser mesh toward the vapor passage may enable the highest gravity-assist heat pipe performance; however, the use of a screened wick is a costly alternative to simple, knurled or threaded heat pipes.

The effect of liquid inventory and elevation angle seem to play a minor role in the entrainment limit phenomena, at least as long as the mechanism of entrainment is vapor dominated. However, at low powers and temperatures the gravity-assist heat pipes become liquid limited and the inventory and elevation angle become important. A model for this mechanism has been presented.[5]

Hopefully, data obtained by others using gravity-assist heat pipes can be used to clarify some of the uncertainties postulated by this entrainment limit model. We hope this correlation will serve as a starting point for future refinements in the theory.

CONCLUSIONS

1. Entrainment limits in vertical, gravity assist heat pipes are vapor dominated and therefore, are essentially independent of liquid inventory.

2. The entrainment limits can be successfully correlated with a physical model based on a critical Weber number. The correlation is

$$Q_e = \sqrt{2\pi/\alpha}\, E_t^{1/2}\, \delta/\delta^*,$$

   where $\delta^* = 0.067$ cm.

3. The characteristic length in the Weber number formulation is the depth of the wick structure. In the case of screened wicks, one-half the wire diameter of the innermost layer is used.

4. The existence of a critical surface depth is postulated beyond which the influence of the underlying surface is diminished.

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